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Non-destructive testing：the guarantee of the success of full scale aircraft fatigue test

Rong S GENG

Beijing Aeronautical Technology Research Center, Beijing 100076，China

E-mail: gengrs@sohu.com

Abstract

The full scale aircraft fatigue test（FSAFT）is crucial for determining the fatigue life (or service life based on flight hours) of an aircraft group and for understanding its performance during whole service life. So far, FSAFT is the only means in correctly obtaining the fatigue life of an aircraft group. The early locating and finding repairable cracks and damages in critical structures of the aircraft during fatigue test is the key factor for the successful fulfillment of the test and for the correct determination of fatigue life of corresponding aircraft group. The comprehensive application of effective non-destructive testing (NDT) means, together with acoustic emission real time monitoring during the process of the entire test was shown to be the guaranteeing factor for the success of the FSAFT. The technical details of NDT of aircraft critical structures during full scale fatigue test were introduced. Descriptions were specially given to the acoustic emission (AE) monitoring and early damage prediction. Case studies included the monitoring of the central wing, and the central wing/outer panel jointing areas. New approaches to the AE data processing were employed because of the requirement for the real time and in-time monitoring of the structures throughout the fatigue test. Due to the extremely long time period spanned by the test, say 3-4 years, data acquisition and processing was faced with very high challenges. By using the combination of trend analysis of statistic AE parameters, time-based and amplitude-based filtering, and spatial filtering techniques, together with multi-parameter identifications, real time and in-time monitoring of the critical structures was realized, proving the effectiveness of current methods. The integration of NDT means with AE monitoring played key roles for the fulfillment of the FSAFT.

Keywords Full Scale Aircraft Fatigue Test Non-destructive testing (NDT) Acoustic Emission (AE) Fatigue life

1 Introduction

The full scale aircraft fatigue test (FSAFT) was of significance for the evaluation of fatigue damage development during life-long operation period of an aircraft group and hence for the determination of its service life based on flight hours. The FSAFT was also very important for lead aircrafts of the group. The non-destructive testing carried on throughout the fatigue test was essential for the understanding of the initiation and development of fatigue cracks in critical parts of the aircraft. Unless proper measures were taken before a critical crack size was reached, the fatigue test might be subjected with a failure. In addition to conventional NDT means, such as UT, ET, RT, MT, PT, endoscope and magnetic memory test, the AE technique was used to monitor most of critical structures inaccessible for the conventional NDT. All these measures played a significant role in assessing the aircraft fatigue life, its maintenance and overhaul cycles, and especially for future modification and improvement of the aircraft. FSAFT was a compression of the life-long service of the aircraft in the time scale . It was even appropriate to say that NDT carried in the fatigue test was fully representative of the NDT in its life-long period of the aircraft group. So specified NDT was also a text book of field NDT of the aircraft, and also a guideline for the instruction of future NDT procedures.

For the specific location under monitoring, it was important to design NDT scheme and procedure, and to use a principal NDT method plus one more at least additional secondary method to provide high reliability of detection. Moreover, the visual inspection (including video endoscope inspection) should not be neglected because of its advantage for large area and rapid inspection.

The FSAFT included five subsidiary tests: the functional test of operation system, the controlling test of landing gears, test of landing gear doors, test of airframe components under flight loading condition, and test of airframe under grounding loading conditions. It was not difficult to imagine that the locations under supervision and the size of workload were rather large, even beyond the capability of manpower. It was therefore significant to simplify and optimize the locations to be monitored, based on the opinion of specialists in structures. In addition, it was also very important to determine the schemes for mounting sensors, to test the sound wave propagation medium, to evaluate the stability of whole system, and most importantly, to investigate the background noise and to find an effective means to identify useful AE signals from background noise. It was only after all these measures had been worked out, the NDT work and AE monitoring during FSAFT could be possibly leading to a success. The purpose of the paper was to present the work of present author in this respect.

2 Pre-test preparation work

Taking airframe components test under flight loading condition as an example, the numbers of positions under monitoring were over 60, among which many were inaccessible. The difficulties faced by the NDT and AE work were therefore beyond imagination. However, the key areas were the central wing and outer panel jointing area, especially the No.1, No.2 and No.3 walls, the Φ14 and Φ12 mm bolts and bolt holes in the walls, referring to figure 1, where L and R wings were left and right outer panels, respectively, and C wing was standing for the central wing. For the airframe test under grounding loading conditions, the critical areas were the upper and lower webs and beams of the main landing gears. The work of AE monitoring was followed in eight steps as described below.

Step 1：to correctly select mounting positions of sensors and confirm there were proper propagation paths for sound waves;

Step2: to select parameters of the instrument, including the threshold V_t, PDT, HDT and HLT;

Step3: to investigate AE characteristics of simulated sample (same material as the structure);

Step4: to investigate background noise and to determine which statistic parameters were more stable;

Step 5: to produce a mixture signal of simulated AE with background noise and to investigate its characteristics;

Step 6: to find method of extracting simulated AE from signals produced by step 5;

Step 7: to investigate fatigue crack-related AE and its identification;

Step 8: to build up a fatigue crack prediction system.

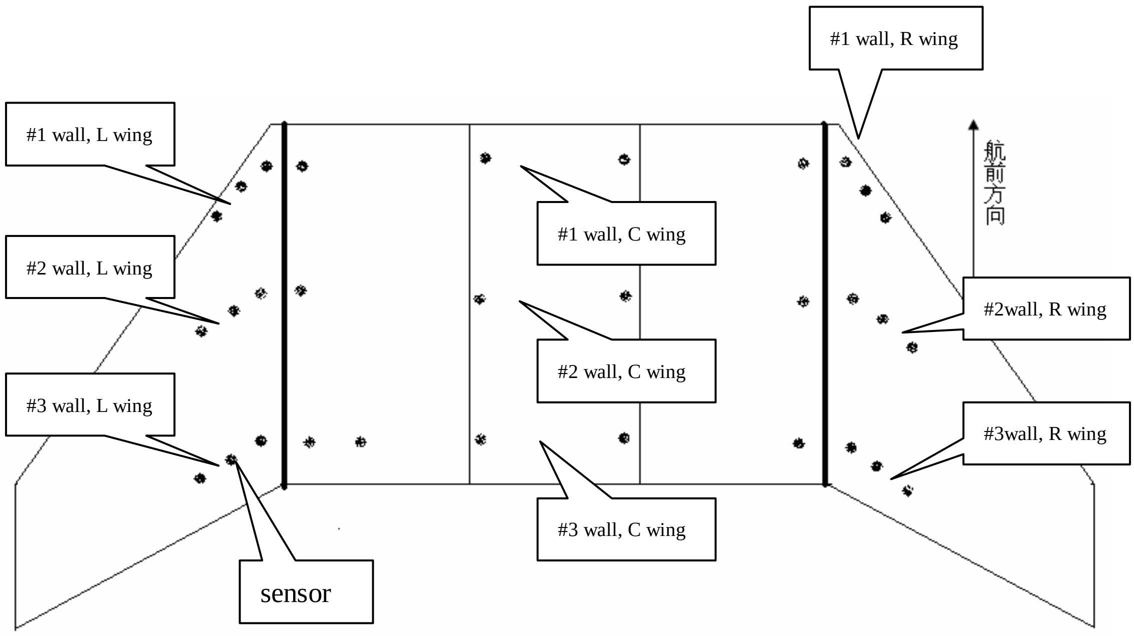


Fig. 1　Schematic diagram of the structures and sensor positions

3　Key elements for data acquisition and processing

3.1　system parameter setting-up

DiSP system of PAC was used for AE testing, with the threshold value being 40-46 dB, depending on the noise level. The gain of preamplifier was 40 dB with the main gain being 20 dB. For channels acquiring waveform, wide-band transducers were used, and the filtering frequency were set in between 100 kHz-2 MHz and the sampling frequency set at 5 MHz， whereas for others, the filtering frequencies were set in between 100 kHz-400 kHz，and the sampling frequency set at 1 MHz. For all channels, the pre-triggering time was set at 32 μs， data length was 1024 points, the PDT, HDT and HLT were 1000,2000 and 5000 μs， respectively.

3.2　data recording

When collecting the test data, it was of importance to record fatigue test time, cycle number, test condition and apparatus state for post-test analysis. In theory, it was better to collect and record data continuously, it was however unrealistic considering the actual capability of both manpower and instrument considering the test lasting time span of 3-4years. Both the crack initiation and its growth should last for some time period, if precautious measures were taken before, the completeness of the data might still be guaranteed without losing too much useful information. The most important step was to have enough data for each loading state, especially for those states under largest load. Normally, each data collecting period lasted for about 15-20 min, and not less than 8-10 times of collecting was realized per day, in realistic time interval. Although the data were collected and recorded discretely, the completeness of data and continuity of information could still be guaranteed.

3.3　main AE signal processing methods

Some data processing methods were mentioned before, such as threshold setting, working frequency region, proper PDT,HDT and HLT, etc. Some other special methods were given below.

3.3.1 load filtering

Load filtering is generally based on the Kaiser effect and it says that the AE occurs only at the stress level higher than previous one during cycling test of a material. The fatigue damage is therefore appears mainly at the higher tensile stress stages during the fatigue test. A predetermined load gate was used where the AE data acquisition started only after the load was higher than that value. By doing so, the signal to noise ratio was greatly increased. The memory space for saving the data was thus reduced to one third of the original ones, according to the authors' experience.

The author developed another concept of load filtering, in which AE data in the same specified load range in the due course of fatigue test were combined as the same group. The statistic averages of so obtained certain AE parameter were chosen as the variable of AE trend analysis and its abrupt change was as the indicator of the fatigue damage.

3.3.2 waveform analysis

The sound wave propagation paths were rather complicated in many critical structures, resulting in the distortion of sound waveforms received by the sensors. Cautions were taken in using waveform to obtain valuable information. Based on the theoretical analysis, cracking was taking place in plane, and hence AE produced by crack was more or less extensional wave predominant, whereas noises were low frequency predominant, or similar with the flexural wave. It was our suggestion to shift the monitoring frequency region above 100 kHz. In some cases, it is useful to use RMS value at one higher frequency range (HF), and the other RMS value at relatively lower frequency range (LF), and one new parameter of the ratio of HF to LF, and its variation rate during the test were used to monitor the initiation of fatigue cracks. Taking the titanium alloy as an example, AE signal related with fatigue damages showed high frequency (at around 630 kHz) predominance, whereas noises had much lower frequencies. If HF was obtained at around 630 kHz, and LF at below 100 kHz, the ratio HF/LF would be a good indicator for damages of Ti alloy.

3.3.3 other data processing means

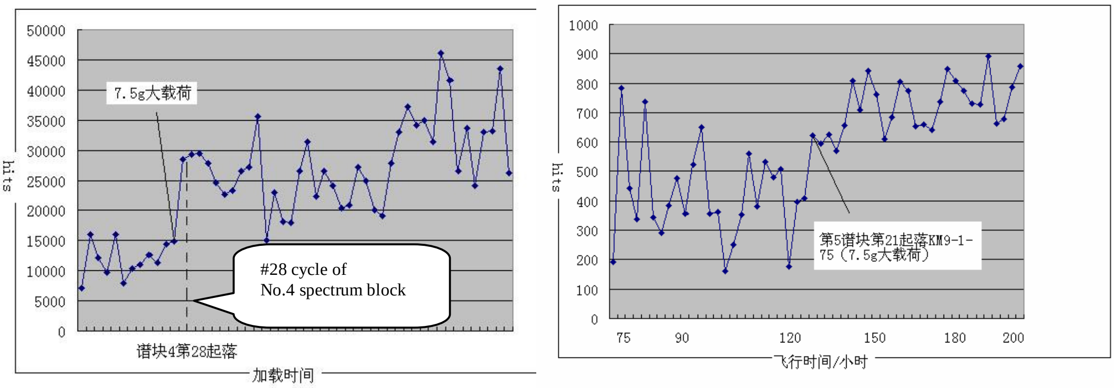
Trend analysis, in which certain statistic variables of AE signals were used as characteristic parameters, was proven an effective means for evaluating fatigue damages in fatigue test. An arbitrary AE parameter, such as AE hit, was changing all the time during the test, it possessed statistical character, however. It was the statistical characteristics that made the parameter a useful variable for evaluating system condition. Trend analysis alone was not enough without other means to support. Therefore, time-based, amplitude-based, energy-based, and spatial position-based filtering techniques, individually or integrally, were used together with multi-parameter identifications method. These approaches played key role in the data processing and in the realization of real time and in-time monitoring of critical structures throughout the fatigue test.

4 Case studies – real time AE monitoring of typical structures

4.1 AE monitoring of right #× wall of central wing and outer panel jointing areas

Random spectrum loading was one of loading methods which most likely simulated the actual loading conditions of aircraft. One of AE early warning of right #× wall failure of central wing and outer panel jointing areas might be the most encouraging case. Before No.4 spectrum blocks of tests, AE signals showed no abnormality, whereas when the test was entering #×× cycles of No.4 spectrum block(S.B), AE from right #× wall was changed greatly,

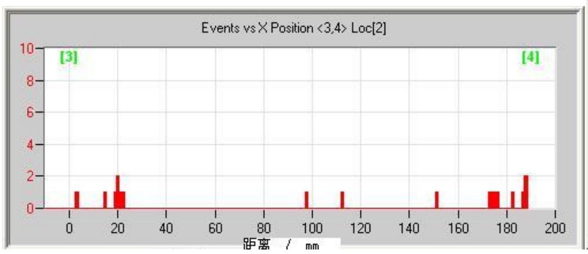
Fig.2 (a) . Afterwards, the abnormal AE signals was maintained for some time period, and went up dramatically after No.21 cycle of #5 spectrum block, Fig.2(b). In Fig.2(b), AE signals with amplitude below 55dB was filtered out, the appeared AE hit number was lower compared with Fig.2(a).

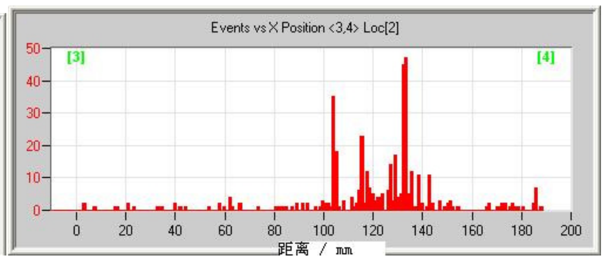


X; loading time; Y: AE hits X; flight time/hour; Y: AE hits

Fig.2 The abnormal increment of AE signals in between #4 and #5 spectrum blocks

In Fig. 3 and 4 were shown the increments of AE location events from cycle 28 to 64 of No.4 spectrum block, corresponding to the damage situations of #× right wall. At around that time, cracks inside the wall was starting to growth.





X: position/mm; Y: AE event number X: position/mm; Y: AE event number

Fig.3 location graph at No.28 cycle of #4 S.B Fig.4 location graph at No.62 cycle of #4 S.B

Later inspection during the stoppage of the test found that the low belly plank of No.7 rib of right #× wall cracked together with a Φ12 mm bolt hole nearby. A detailed inspection found a crack of length of about 20 mm in the lower belly plank of central wing, Fig.5. According to AE results, it was concluded that the bolt hole started to crack at about No.28 cycle of #4 spectrum block, when heavy loading of 7.5 g was exerted upon the aircraft body, and the crack started to grow rapidly after No.62 cycle of #4 spectrum block.

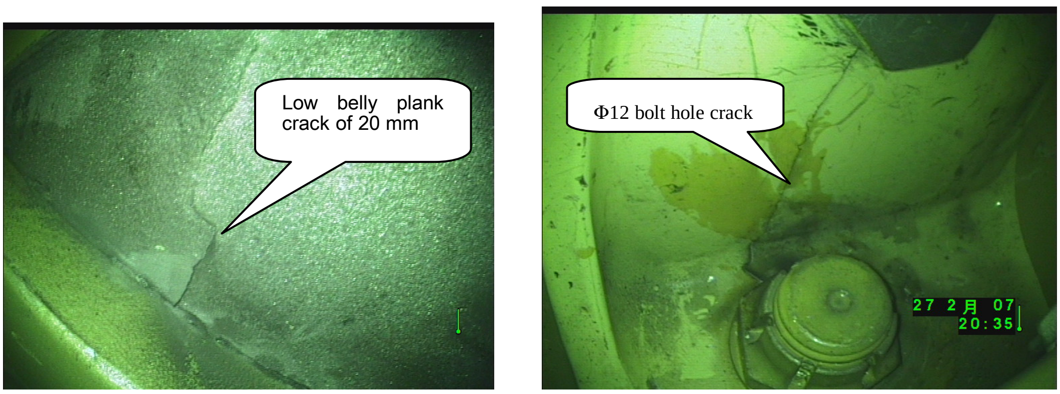
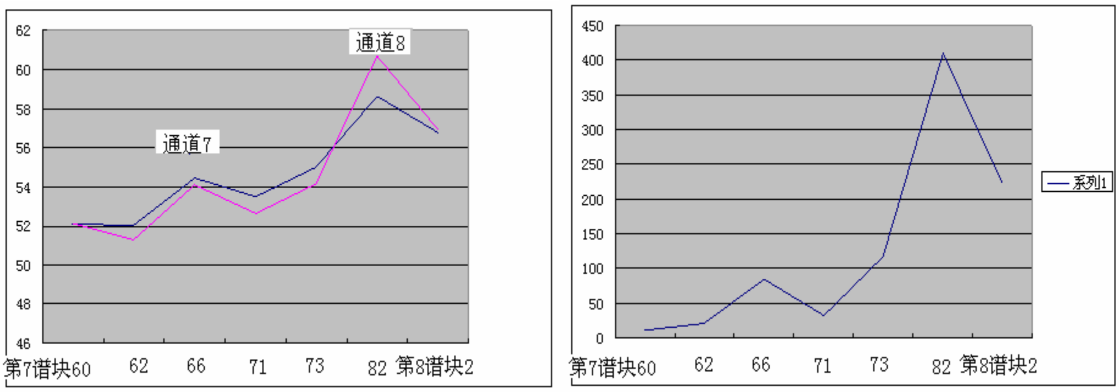


Fig.5 cracks at low belly plank of #× right central wing wall and at Φ12 mm bolt hole

4.2 Early detection of cracks in right #× wall of central wing

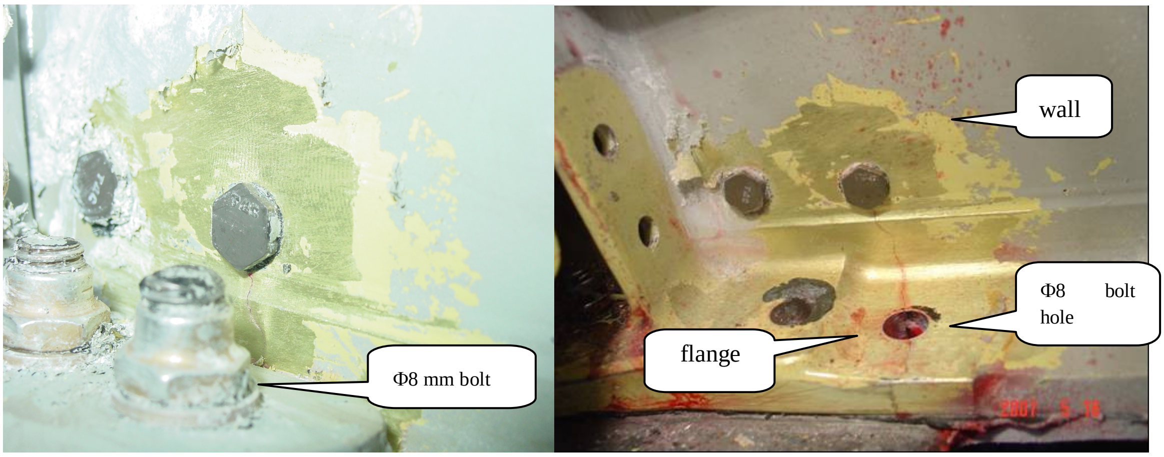
Just a few testing cycles being passed since the repairing of the above-mentioned cracks, AE signals once again issued a warning sign in another central wing wall, where AE hits and events showed an abrupt increment, as shown in Fig 6.



(a) trend of AE hits against test cycle (b) AE event changes after spatial filtering

Fig.6 Abnormal AE changes during FSAFT at certain stages

A fatigue crack of length of 20 mm was found in the bulge of #× wall after a thorough inspection of this area, as shown in Fig.7.



(a) original state of the crack (b) after removing the bolts and dyeing penetration test

Fig 7 confirmation of cracks by AE prediction using other NDT means

5 Conclusions

The non-destructive testing and AE monitoring of critical structures of an aircraft during its full scale fatigue test was faced with difficulty of inaccessible structures, high background noises, complicated sound wave propagation path, and high attenuation of sound wave. The work therefore was met with high challenges and high risks. A principal NDT means was in general followed by an additional NDT method in order to raise NDT reliability. AE monitoring always played important role for those difficult-to-access structures. Real time and in-time monitoring of these critical structures was possible to realize through proper selection of AE sensor positions, by using proper sensor mounting schemes, by carrying on sound wave propagation testing, and by studies of AE characteristics of the material under investigation. For a test whose time span was over several years and places to be monitored were as many as over 60, new approach to AE data processing was needed. Present means of using the combination of trend analysis, time-based, amplitude-based, and spatial filtering techniques, individually or integrally, together with multi-parameter identifications were proven successful. The successive prediction of a few critical cracks in central wing area, together with early detections of fatigue cracks in other critical parts proved the effectiveness of current methods.

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